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MEASURED NET ENERGY PERFORMANCE OF SINGLE GLAZING UNDER REALISTIC CONDITIONS

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ABSTRACT

A new measuring facility, the MoWiTT, has begun operation with a study of the summer performance of single glazing in south-facing and east-facing orientations. These measurements demonstrated the MoWiTT's capabilities and provided a baseline for future measurements of more complex fenestration systems. The net heat flow through the fenestration was measured at fifteen-minute intervals over several days. Simultaneous measurements of air temperatures and solar intensities were used as input data for an ASHRAE calculation of the same quantity, assuming standard summer values for the film coefficients. Good agreement between measured and calculated heat flows was obtained when the vertical surface solar intensity was used as input and the calculation included the effects of window setback.

INTRODUCTION

The energy impacts of fenestration on a building are normally calculated from the internal and ambient air temperatures and the incident solar flux using U-values and shading coefficients as defined by ASHRAE (1985). The use of this methodology to predict peak loads is well established and noncontroversial. However, in recent years interest has shifted toward a quantitative prediction of average or net performance. These data are important for evaluating the payback from incorporating technical innovations into window products, for comparing different strategies for reducing building energy consumption, and for evaluating product compliance with energy performance standards. Therefore, testing the accuracy of the standard ASHRAE calculations is a high priority.

At Lawrence Berkeley Laboratory we have designed and constructed a large calorimetric facility, the Mobile Window Thermal Test (MoWiTT) facility, which is capable of monitoring fenestrations mounted in a room-like test chamber and exposed to ambient weather conditions. The design, expected performance, and rationale for the MoWiTT have been discussed elsewhere (Klems et al. 1982; Klems 1984, 1984). For present purposes the MoWiTT's crucial property is its ability to provide a direct, nearly instantaneous measurement of the net energy flow through the fenestration. This is derived from an accurate net heat balance on the chamber and includes all the thermal effects of solar gain. (The measurement does not, of course, include the energy which might be saved by using the lighting value of the solar gain to reduce electric lighting requirements, although we plan to add measurements of this effect in the future.) Simultaneously, a wide range of other parameters are measured that might be used as inputs to a predictive algorithm, which can therefore be tested. Alternatively, parameters (such as local wind velocity) that are theoretically capable of modifying the U-value or shading coefficient can be studied and their effects on the net energy flow evaluated. One possible use of this procedure would be the resolution of the controversy surrounding U-value measurement procedures discussed at a recent workshop (BTECC n. d.).

We begin the measuring program of this facility with a study of unshaded single glazing. This is a well-studied system for which the standard calculation is unambiguous. It is natural to examine the agreement between measurement and calculation for this simple case before proceeding to more complex fenestrations, where interpretation of discrepancies will be more difficult.

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EXPERIMENTAL ARRANGEMENT

The MoWiTT consists of a pair of room-sized guarded calorimeter chambers contained in a wheeled portable building frame. A cross section of a calorimeter chamber is shown in Figure 1. During these measurements one of the chambers had a window; the other chamber was closed and held at the same temperature as the guard and the operating chamber.

These measurements were made in late August and early September 1985 in the Livermore Valley, about 50 miles east of San Francisco. The local terrain is flat and extends in all directions to surrounding hills less than 2500 ft (750 m) high. The line-of-sight distance to the hill peaks is about 15 miles (25 kilometers) to the south and west and 5 miles (8 kilometers) to the north and east. The weather was generally hot, with skies varying between clear and overcast. The wind patterns during August are typically cyclical. During the afternoon the wind comes from the west-southwest and averages 12 MPH (19 km/h); at night it comes from the east-southeast and averages 1.9 MPH (3 km/h). Transition between the two wind regimes is rapid, occurring between 0900 and 1200 hours and again between 2000 and 2200 hours. The maximum daytime temperature was about 95^{o} F (35^{o}C) and the diurnal temperature swing was about 30^{o} F (17 ^{o}C).

As indicated in Figure 1, the sample is mounted in a larger test wall that bridges the guard space between the inner and outer walls of the chamber. The sample tested was a 4-ft by 3-ft (1.22-m by 0.92-m) piece of 1/8-inch (3-mm) clear glass mounted with a 0.89-ft (0.27-m) setback in the 4.9-ft x 5.0-ft (1.50-m X 1.53-m) opening of the test wall. The glass was held by a simple frame consisting of 6-inch (150-mm) polyurethane foam faced with 1/2-in (12-mm) exterior plywood on the inner and outer surfaces and 5/8-in (16-mm) redwood on the surfaces adjacent to the glass. The glass was held in place with strips of quarter-round, and the entire assembly was sealed to prevent air leakage. The calculated area-thermal transmittance product for the frame was 0.38 BTUH/F (0.2 W/K), or about 3% that of the glazing.

Two pyranometers were used to monitor the solar flux, while a pyrgeometer monitored the longwave infrared flux from the sky. One of the pyranometers was mounted vertically above the test window; the other was attached horizontally in an oscillating mount that moved it alternately in and out of the shade of a shadow band. This provided a measure of both horizontal total and horizontal diffuse radiation. The pyrgeometer was mounted horizontally. Thermistors measured the air temperature at 13 points in the chamber. The exterior air temperature was monitored with a single thermistor mounted in the shaded space below the MoWiTT.

Data were recorded at fifteen-minute intervals. Solar data and all measurements contributing to the net heat flow were determined as averages over the recording period. The recording period (which is easily changed) was chosen as a compromise between sufficient time resolution and a manageable quantity of data.

RESULTS

The measured and predicted heat flow through the test sample consisting of the glazing plus frame is graphed in Figure 2 as a function of time for the two orientations. The measured heat flow is derived from measurements of the heat added to or extracted from the chamber air and the heat flowing through the test chamber envelope. These data are independent of measurements of temperature or solar flux. The accuracy of this net heat balance was verified by a separate calibration of the calorimeter chamber configured as a closed box. Based on this calibration, the error in the net heat balance is expected to be less than 10 watts during the daytime and 2 watts at night. The sample heat flow is defined as positive for heat flowing into the chamber. As shown, the heat flow varies between a small nighttime heat loss and large daytime heat gain.

Figure 2a presents the measured and calculated net heat flow for two days when the sample faced south. The first day was clear and the second partly cloudy, as can be inferred from the relative magnitudes of the daytime heat gain. Figure 2b shows the net heat flow for a five-day period when the sample faced east. These measurements are characterized by a sharp morning peak, followed by smaller afternoon gain when the window no longer received direct sunlight. On the second and third days the solar peak was significantly attenuated by morning clouds. The afternoon was clear on both days.

The calculated curve shown in the figure is the sum of three separate effects. The first two are the thermal transmittance and the solar heat gain, which are contained in the standard calculation:

$$q_A = [\; U\, A_0 + (UA)_F \;]\, \Delta T + A_E\, [\; \tau + N_i\, \alpha \;]\, I_S \; . \qquad (1)$$

Here q_A is the heat flow through the sample; A_0 and U are the area and thermal transmittance of the glass (U containing the film resistances); $(UA)_F$ is the area-thermal-transmittance product of the frame; ΔT is the outside-inside temperature difference; A_E is the effective (unshaded) aperture of the glass for beam solar radiation, τ and α are the solar-optical transmission and absorption of the glass; N_i is the inward-flowing fraction of absorbed solar energy; and I_S is the incident solar flux. We have used Yellott's (1964) calculation for the inward-flowing fraction,

$$N_i = \frac{U}{h_0} \; , \qquad (2)$$

where h_0 is the outside film coefficient. For each data point, the beam solar incident angle was computed for the glass and Rubin's (1985) values were used for τ and α. The ASHRAE summer values of h_0 = 4.0 BTUH/ft^{2}F (22.7 W/m^2·K) and U = 1.01 BTUH/ft^2 F (5.72 W/m^2·K) were assumed.

For the incident solar intensity, I_S, the measured solar flux from the vertically mounted pyranometer was used. Although in the common usage of Eqn. 1 the solar flux is derived from horizontal measurements because direct measurements of solar intensity on a vertical surface are not generally available, it is known that there are difficulties with this procedure.

The third part of the calculation was developed because of the setback of the glass. Shadowing due to this setback results in a different effective aperture for beam and diffuse solar flux. During significant parts of the day, the aperture for direct radiation, A_E, vanishes. We handled this situation by defining a diffuse correction to the heat flow:

$$q_D = [\; A_0 - A_E \;]\; [\; \tau_H + \alpha_H\, N_i \;]\; I_D \; , \qquad (3)$$

Where we have approximated the diffuse aperture with A_0, the subscript H on α and τ denotes hemispherical averages, and I_D is the diffuse part of the vertical solar flux. We estimated the beam solar contribution to I_S from the horizontal solar measurements and subtracted the estimate from I_S to obtain I_D. If a negative value was obtained I_D was set to zero (since the estimate is known to be unreliable near sunrise or sunset). For times and orientations when direct sunlight could not shine on the vertical pyranometer (e.g., afternoon for east-facing), I_D was taken to be equal to I_S.

The contribution of the three parts to the calculated curve is shown for selected days in Figure 3.

DISCUSSION

Figures 2 and 3 show that agreement between the measurements and the calculated curve is excellent. There are, however, two minor disagreements. First, the measurements appear to lag behind the calculated curve slightly. We believe this is due to the thermal mass of the portion of the calorimeter inside the heat-flow sensors. A time lag of the order of one-half to one hour is consistent with other observations made during calibration of the chamber. No correction is as yet being made for it. A shift of this magnitude would place the calculated curve symmetrically with respect to the measured curve around solar noon, as one would expect. We note that an hour (or half-hour) time lag is already short compared to the thermal lag time of normal buildings; however, we expect that improved analysis will give still better results.

Second, the calculated curve systematically underestimates the measured one near solar noon, differing by some 20% on clear days. If genuine, this disagreement would be difficult to account for theoretically, since one would expect the theory to do best at just these times. We believe that at least a substantial part of this difference is due to reflection of sunlight into the window from the sills created by the setback of the test sample. These sills were painted white at the time the data were recorded. A rough estimate of diffuse reflection from this source yields an expected 10% increase in the heat flow at solar noon. Whether this will suffice to explain the observed excess must wait on a more careful study of this effect.

CONCLUSIONS

We conclude that the MoWiTT provides easily interpretable data of high quality, with good time resolution. For single glazing under specific summer conditions, the data from the MoWiTT are in substantial agreement with the predictions of the standard ASHRAE theory using measured values of the incident solar flux on the window plane. Minor disagreements observed may be due to instrumental effects and should not be considered significant. More subtle effects expected theoretically, such as variation of film coefficients with wind, have not yet been investigated.

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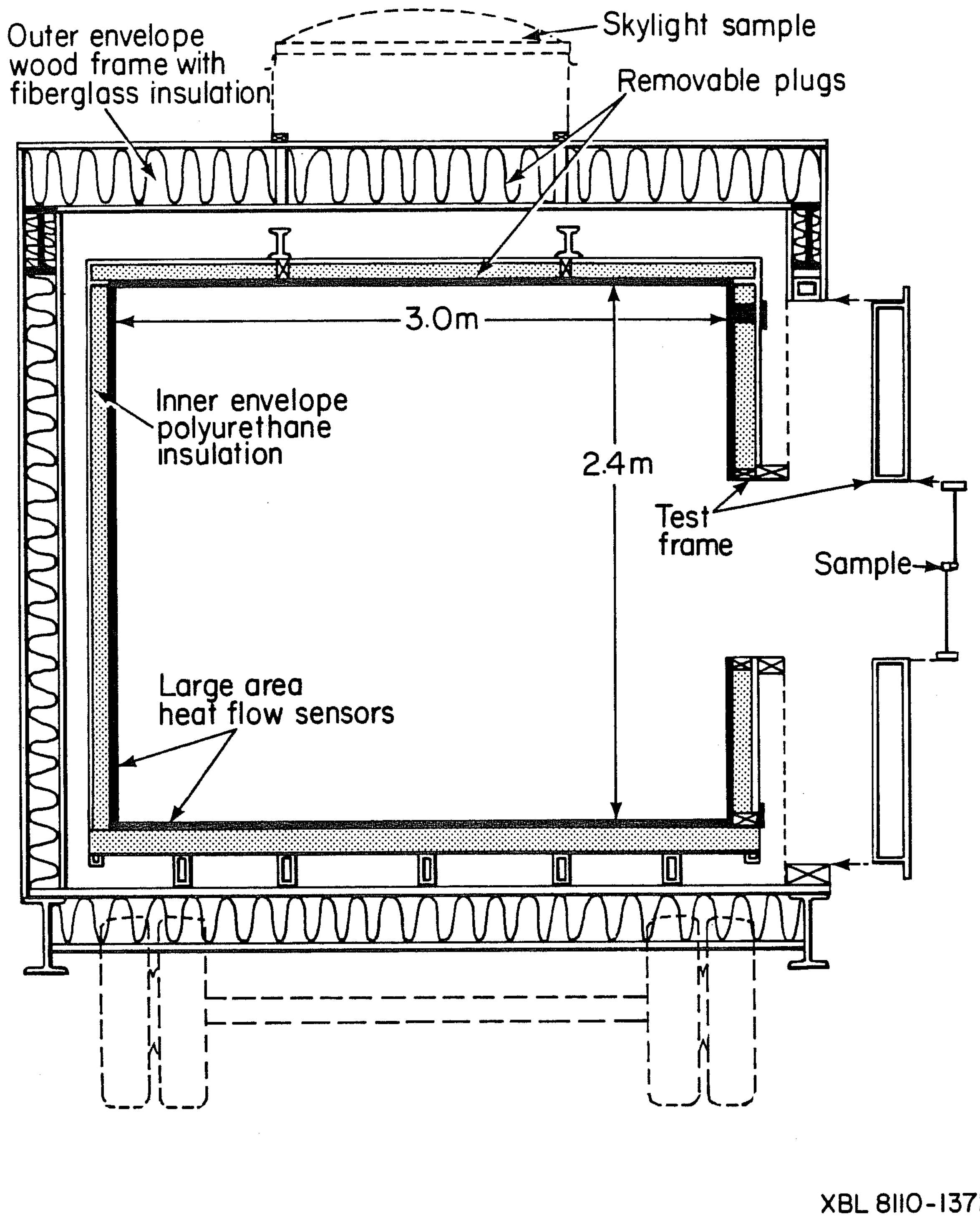
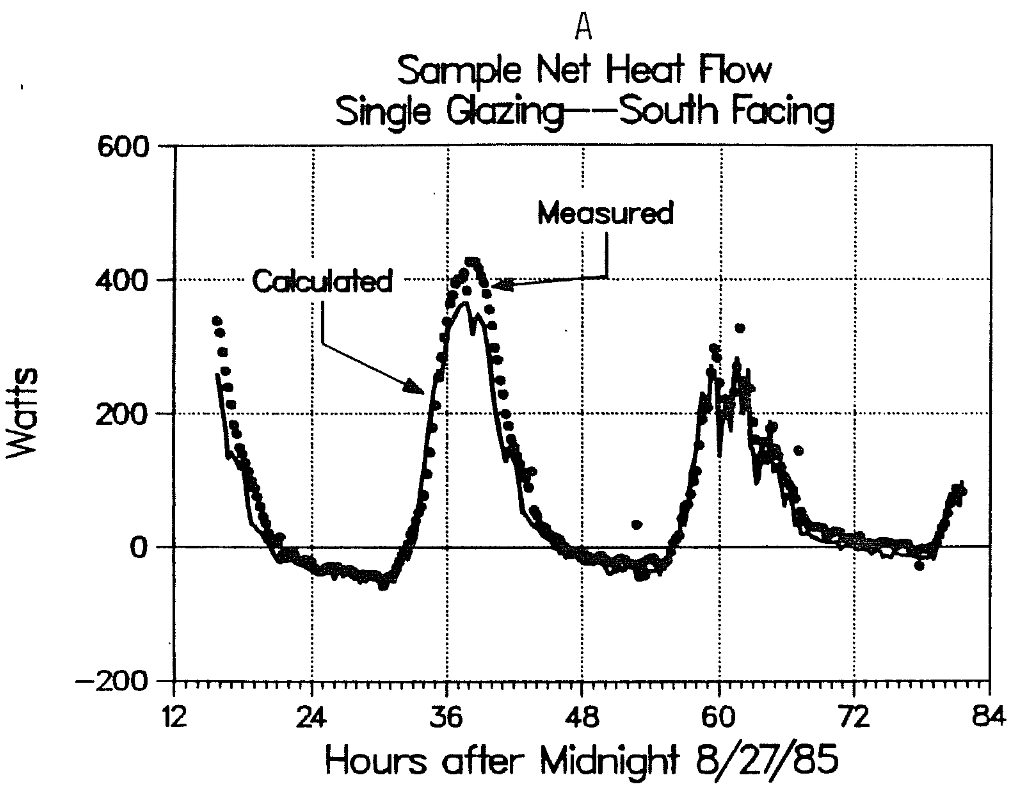


Figure 1. Cross Section of MoWiTT Calorimeter Chamber.



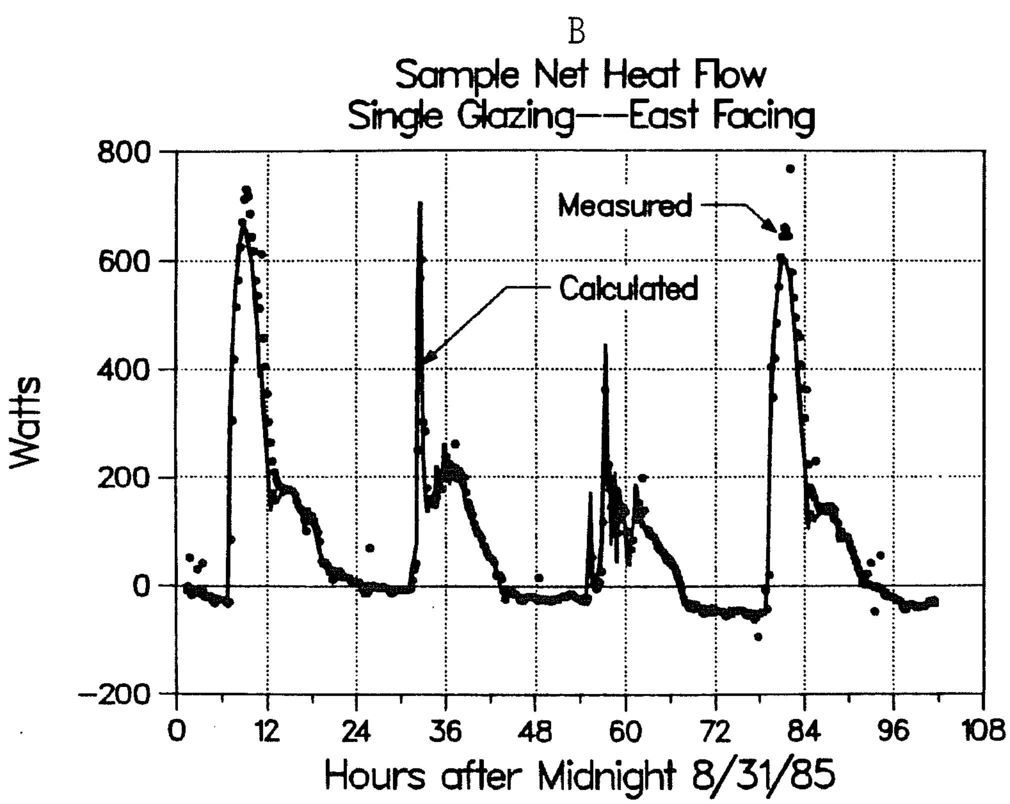
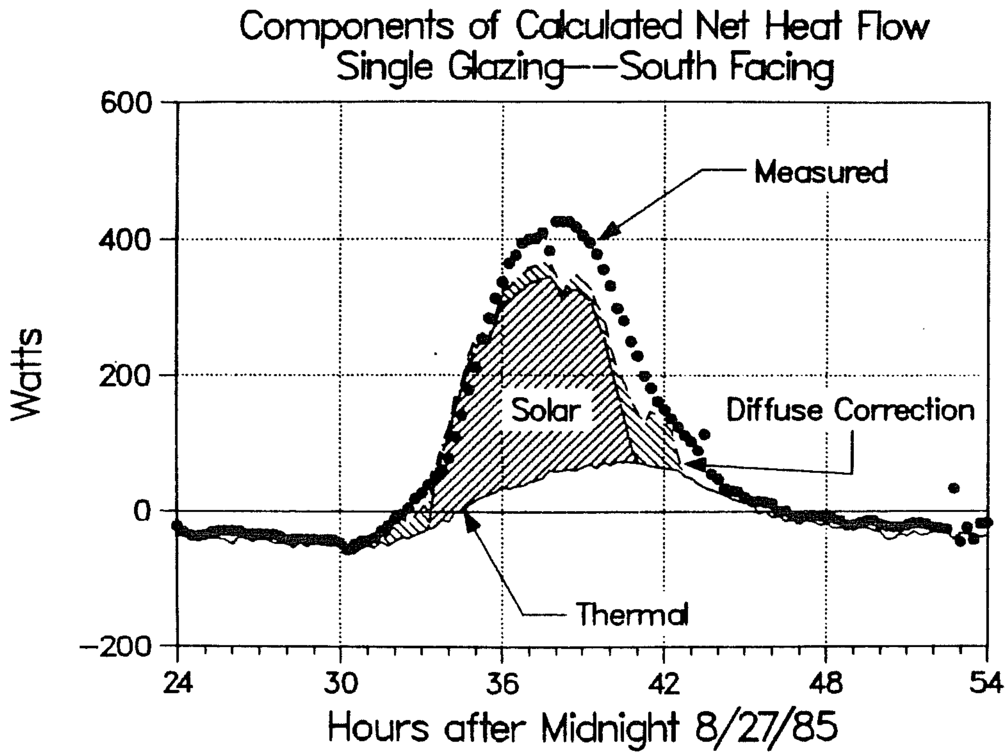


Figure 2. Measured net heat flow through the fenestration: (A) south-facing orientation; (B) east-facing orientation.

A



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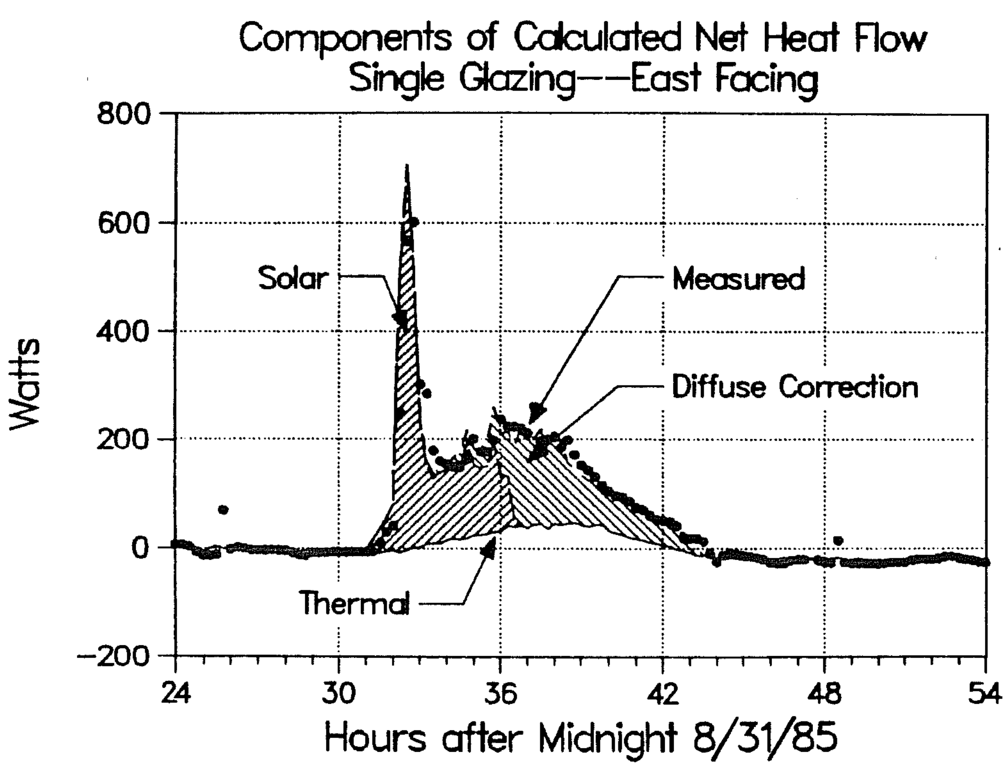

Figure 3. Components of the calculated net heat flow: (A) south-facing orientation, day 1; (B) east-facing orientation, day 2.